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ORIGINAL PAPER

The spatial-temporal pattern and influencing factors of negative air ions in urban forests, Shanghai, China

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Abstract: Negative air ions are natural components of the air we breathe. Forests are the main continuous natural source of negative air ions (NAI). The spatio-temporal patterns of negative air ions were explored in Shanghai, based on monthly monitoring in 15 parks from March 2009 to February 2010. In each park, sampling sites were selected in forests and open spaces. The annual variation in negative air ion concentrations (NAIC) showed peak values from June to October and minimum values from December to January. NAIC were highest in summer and autumn, intermediate in spring, and lowest in winter. During spring and summer, NAIC in open spaces were significantly higher in rural areas than those in suburban areas. However, there were no significant differences in NAIC at forest sites among seasons. For open spaces, total suspended particles (TSP) were the dominant determining factor of NAIC in summer, and air temperature and air humidity were the dominant determining factors of NAIC in spring, which were tightly correlated with Shanghai's ongoing urbanization and its impacts on the environment. It is suggested that urbanization could induce variation in NAIC along the urban-rural gradient, but that may not change the temporal variation pattern. Furthermore, the effects of urbanization on NAIC were limited in non-vegetated or less-vegetated sites, such as open spaces, but not in well-vegetated areas, such as urban forests. Therefore, we suggest that urban greening, especially urban forest, has significant resistance to the effect of urbanization on NAIC.

Keywords: negative air ion concentration, spatial-temporal pattern, urbanization, urban ecosystem, urban greening

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Introduction

Negative air ions (NAI) are natural components the air we breathe (Kosenko et al. 1997). When sufficient force displaces an outer electron from a molecule of common gases, such as oxygen and nitrogen, the free electron is promptly picked up by an adjacent molecule, which then becomes negatively charged. Meanwhile, the residual molecule is left with a positive charge. These molecular ions are soon attracted to water molecules and uncharged gaseous molecules in the air, which form singly charged molecules (Krueger 1985). Superoxide (O^{2-}) is the main negatively charged species of NAI (Goldstein et al. 1992; Kosenko et al. 1997; Wu and Lee 2004) and is more stable than other ions.

In nature, NAI can be generated by the minute shearing of water droplets, radioactive components of soil, cosmic radiation, ultraviolet rays, coronal discharge or lightning, and forests (Krueger and Reed 1976; Yates et al. 1986; Iwama 2004). Of these, forests are the main continuous natural source of NAI (Wang and Li 2009), because leaf tips have a photoelectric effect during photosynthesis, which are able to promote electrolysis and produce large quantities of NAI (Tikhonov et al. 2004). In addition, aromatic substances released by forests, such as phytoncide, can also promote air ionization and increase negative air ion concentrations (NAIC) (Shao et al. 2005; Bai and Wu 2008). Additionally, NAI can also be produced by artificial combustion sources, hot surfaces, and flames, such as motor vehicles and power lines (Fialkov 1997; Maricq 2006; Peineke and Schmidt-Ott 2008; Ling et al. 2010).

Under stable conditions, the background level of NAIC is in the magnitude of hundreds (Hõrrak et al. 2003; Vana et al. 2008), usually about 300–400 ions/cm^3 (Ling et al. 2010). NAIC can increase to the magnitude of thousands in the presence of natural or anthropogenic ion sources, such as forests (Wu et al. 1998),

waterfalls (Laakso et al. 2007) and overhead power lines (Jayaratne 2008). Wu et al. (1998) measured NAIC in *Pinus massoniana*'s pure forest in the Hengshan Mountains and found that NAIC varied from 1200–2000 ions per cm^3. NAIC ranged from 2000 to 10,000 ions/cm^3 near waterfalls (Iwama 2004). However, NAIC decreases considerably or even falls to zero in polluted air (Tikhonov et al. 2004).

Because the typical lifetime of NAI in clean air is less than several minutes (Daniels 2002), NAIC are not consistent or stable in the natural environment and exhibit noticeable fluctuations under different temporal scales, which has been widely documented in many studies (Tammet 1995; Hõrrak et al. 2003; Retalis and Nastos 2009; Pawar 2010). For example, Dhanorkar and Kamra (1993) analyzed diurnal and seasonal variations in the concentrations of ions in Pune, India from February 1990 to January 1991. They found that peak values of NAIC occurred in the morning and were higher during the nighttime than during the daytime. The same study found that NAIC was higher in winter than in other seasons. Retalis and Nastos (2009) analyzed the diurnal, monthly and seasonal variations in NAIC in Athens, Greece from 1968 to 1984, and found the maximum values occurred around the summer.

NAIC prominently depends on humidity, temperature, wind, and air pollution (Li et al. 2013; Vana et al. 2008; Wu et al. 2011). Retalis (1977) indicated that particulate air pollution (smoke), gaseous air pollution (sulphur dioxide or SO_2), photochemical pollution (i.e., NO_2, O_3) and wind speed had great impacts on atmospheric electrical parameters. Retalis et al. (1991) revealed that NAIC were positively correlated with wind speed but negatively correlated with relative humidity, smoke, and sulphur dioxide.

NAI are termed "air vitamins" as they have an important biological influence on various micro-organisms (Rosenthal et al. 1979; Shargawi et al. 1999) and positive effects on humans (Takahashi et al. 2008; Kolarž et al. 2009). Therefore, higher NAIC can improve lives in urban regions. Previous researchers have shown that the NAIC in forests or woodlands were higher than in control sites without ion sources (Ling et al. 2010; Pan and Dong 2010), which suggests that forests can be considered as a major stable source of NAI (Wang and Li 2009) in urban areas.

However, urbanization could change the micro-climate, such as urban heat islands (Zhang et al. 2010), and cause air pollution which might offset the NAI. The results of Tikhonov et al. (2004) indicated that the NAIC is lower in industrial areas than in rural regions. Therefore, it is necessary to check the NAIC of forests along the urban-rural gradient, which have been considered an indicator of population, land use, and environmental quality (Chen et al. 2006; Pan and Dong 2010).There has not been such a detailed study until now.

China has been undergoing a period of economic reform and expansion since the late 1970s, accompanied by rapid and widespread urbanization. Shanghai is the largest city in China and has the highest level of urbanization. During rapid urbanization, different environmental gradients have been shown to emerge along the urban-rural gradient in Shanghai, such as surface water quality (Wang et al. 2008), air quality (Zhao et al. 2006), urban heat island effects (Zhang et al. 2010), and biodiversity (Zhao et al. 2006). We suspected NAIC would follow a pattern similar to these environmental variations. In this study, we focus on two questions: Do NAIC show variations along the urban-rural gradient? If so, what are the dominant factors affecting NAIC?

Materials and methods

Study area

Shanghai (31.1°N, 121.4°E), situated on an alluvial plain at the mouth of the Yangtze River, is the largest city and the most economically prosperous region in China. With a population of over 18 million, the municipality occupies an area of approximately 6400 km^2, of which 697 km^2 is composed of water. Influenced by a subtropical monsoon climate, it has a distinct seasonal temperature pattern with a mean annual temperature of 18°C and a mean annual rainfall of approximately 1158 mm.

Following the circle-sprawl process of urbanization (Li et al. 2012; Kuang et al. 2014), Shanghai can be divided by its ring roads into urban (innermost), suburban, and rural (outermost) areas. The urban area (U) is within the inner ring road, and covers 13 administrative districts (Baoshan, Yangpu, Hongkou, Zhabei, Putuo, Changning, Xuhui, Pudong new area, Huangpu, Luwan, Jingan, Minhang, and Jiading) with a total area of 114.9 km^2. The suburban area (S) is between the inner ring road and the outer ring road, and covers seven administrative districts (Baoshan, Jiading, Qingpu, Songjiang, Minhang, Fengxian, and Pudong new area) with a total area of 557.6 km^2. The rural area (R) is outside the outer ring road, and covers seven administrative districts (Baoshan, Jiading, Qingpu, Songjiang, Fengxian, Jinshan and Pudong new area) with a total area of 4231 km^2.

Methods

Overall, 15 parks were selected as study sites along the Shanghai urban-rural gradient, of which four were located in urban areas, seven in suburban areas and four in rural areas (Fig. 1). All were considered middle-size, with area of 5.23±2.89 km^2 (mean±SD; Table 1). All of the selected parks were far away from high-voltage transmission lines and large rivers (the Huangpu River and Suzhou River) due to their effect of increasing NAIC.

In each park, forests and open spaces were selected as sampling sites for experimental observations. Forest sites were composed of woody trees with canopy heights greater than 8m. Open space sites were without any vegetation. Based on previous studies, different tree species have distinct effects on NAIC (Wang and Li 2009). Therefore, all selected forests were dominated by *Cinnamomum camphora* with areas greater than 400m^2. Meanwhile, the open space sites were at least 10m away from the forests. To avoid other ion sources, all monitoring sites were in the center of parks and more than 20m away from rivers or ponds.

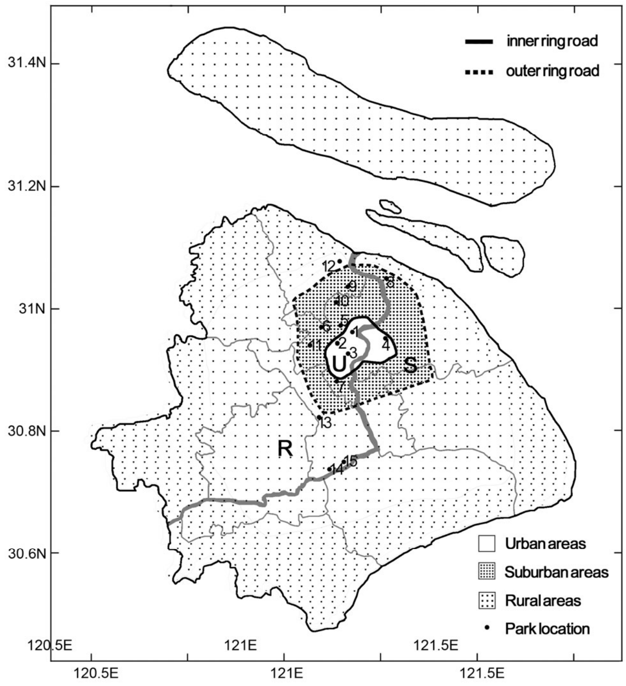

Fig.1: Location of the 15 sampling parks in Shanghai. The number 1-15 is the park ID.

Table 1: The list of parks sampled in our study. Parks were divided into three groups based on their location within Shanghai: urban areas, suburban areas and rural areas. All parks were middle-size parks in Shanghai with an area of 5.23 ± 2.89km^2 (mean ± SD).

Park ID	Park name	Area (km^2)	Location
1	Chuanbei Park	4.24	Urban area
2	Changshou Park	4.11	Urban area
3	Fuxing Park	8.89	Urban area
4	Jingnan Park	2.24	Urban area
5	Zhabei Park	13.2	Suburban area
6	Dahua Park	5.8	Suburban area
7	Caoxi Park	3.13	Suburban area
8	Gaoqiao Park	4.64	Suburban area
9	Songnan Park	8	Suburban area
10	Sanquan Park	2.72	Suburban area
11	Xianghe Park	3	Suburban area
12	Youyi Park	4.41	Rural area
13	Xinzhuang Park	3.88	Rural area
14	Hongyuan Park	4.08	Rural area
15	Minhang Park	6.06	Rural area

NAI were measured at a height of 1.5m (about the height of people's breath) above ground in the center of each monitoring site. All measurements were carried out during three time periods: 8:00-11:00, 11:00-14:00 and 14:00-17:00 on days with clear weather. Due to the impact of continuous rainfall in July-August 2009, measurements in these months were grouped into one set. For each park, all monitoring sites were measured at the same time for one day per month from March 2009 to February 2010. Air temperature, air humidity, wind speed, and total suspended particles (TSP) were measured simultaneously.

Meanwhile, the number of persons who passed the monitoring site within 5 m of the measurement points was recorded to evaluate the effect of human disturbance. Smokers were asked to avoid the area, to ensure accuracy of the measurements. The air content of SO_2, NO_2, and inhalable particulate matter (PM10) were collected from the observations collected from a nearby environment monitoring station managed by the Shanghai Environmental Protection Bureau (2009-2010).

Instrumentation

Air ion concentrations were measured by two ITC-201A air ion counters (ANDES, Japan) that were factory-calibrated just prior to the field measurements. These instruments have a dynamic range of 10-1.236×10^6 ions/cm^3 with a minimum detectable charge concentration of 10 ions/cm^3. Because the instrument can measure the negative and positive ions separately, two instruments were used to measure both positive ions and negative ions simultaneously at each monitoring site. The time of each measurement was set to 10 minutes. Air temperature and humidity were measured concurrently with air ions by the same instrument, and the mean of the two instruments was used for analysis. The 10-minute wind speeds were measured by an AZ8904-type speed control (Taiwan HengXin Technology). The measuring range of the instrument is 0.4–35m/s and the accuracy degree is 2％. The resolution is 0.01m/s. Total suspended particles (TSP) were measured by a P-5L2C portable microcomputer dust monitor (Peking, China). The measuring range of the instrument is 0.01-100mg/m^3.The detection limits was 0.01mg/m^3.

Data analysis

One-way analysis of variance（ANOVA）was used to analyze temporal and spatial patterns of NAIC in forests and open spaces with *p*-level <0.05 considered statistically significant. In order to examine factors affecting NAIC in spring and summer, a multiple regression analysis was applied. These factors included: air temperature, air humidity, total suspended particles (TSP); inhalable particulate matter (PM10); wind speed; SO_2; NO_2; and the total number of people passing within 5m of the measurement points.

Daily mean values of all of these parameters were applied in the analysis. The contribution of each independent factor to the predicted variable is described by the regression coefficients (B-coefficients), and the relative importance of each factor compared to the other factors is described by the standardized regression coefficients (Beta-coefficients). The statistical significance of the factors is represented by their p-values. The regression coefficients (Beta-coefficients) represent the independent contributions of each independent variable to the prediction of the dependent variable.

Results and discussion

A total of, 990 10-minitue mean values of NAIC were measured in 15 parks over one year. The maxima value and the minima value were 2050 ions/ cm^3 and 10 ions/cm^3, respectively. The mean values and standard errors were 502 ions/cm^3 and 10 ions/cm^3, respectively. Standard deviation and variance of NAIC were 286 ions/cm^3 and 82 ions/cm^3, respectively. Because there were no significant differences among the three monitoring periods in a given day for both forest sites and open spaces, daily mean value were used in the following analysis.

Annual variations of NAIC

The annual variation in NAIC for forests and open spaces are summarized in Fig. 2a-b. Peak values of NAIC for forests clearly occurred during June to October, while the lowest NAIC were observed during December to January (Fig. 2a). A similar pattern was observed in open spaces (Fig. 2b). The maxima values of NAIC for forests and open spaces were 919 ions/cm^3 and 713 ions/cm^3, while the minima values were 162 ions/cm^3 and 143 ions/cm^3 respectively. The mean values of NAIC for forests and open spaces were 521 ions/cm^3 and 452 ions/cm^3, respectively.

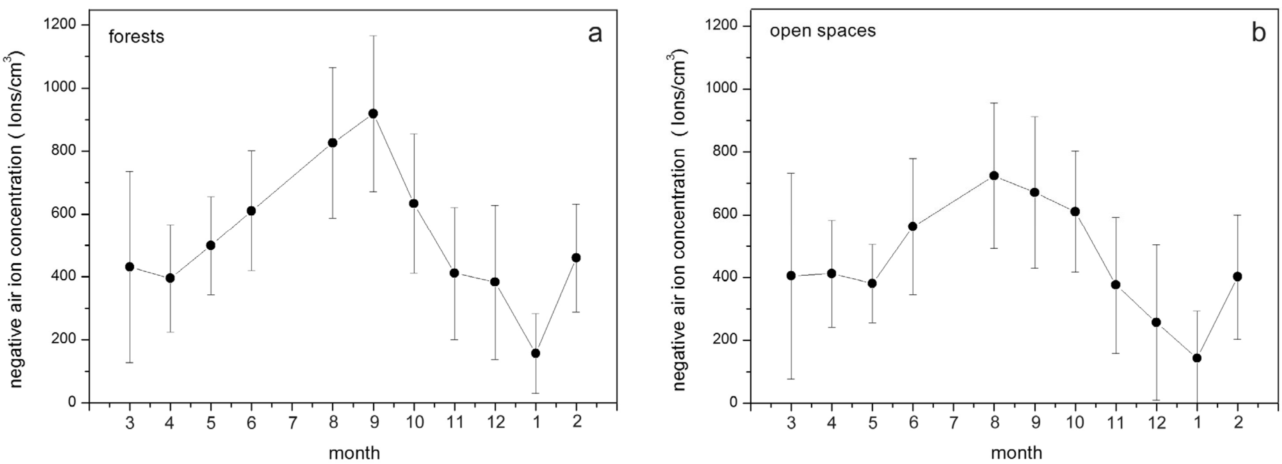

Fig. 2: Annual variations in negative air ion concentration (NAIC) (Values are presented as mean ± SD.) in the forests (a) and in open spaces (b)

Using an additional fourteen studies, we performed a meta-analysis of NAIC in urban parks, urban forests, and other urban greening areas（compare with the previous studies of more than one year in Table 2). The results show that forests had a mean value of 512 ions/cm^3 with a range of 424 ions/ cm^3 to 617 ions/cm^3; while open spaces had a mean value of 328 ions/cm^3 with a range of 171 ions/cm^3 to 485 ions/ cm^3. Compared with our results, these previous studies identified one site with higher NAIC than our study, and three sites with lower values among forested areas; there were one site with higher NAIC compared to our results and one site with lower concentration than those found in our study on open spaces. The values of NAIC in our study were therefore within the range of the meta-data. In general, our results were similar to the results from previous studies.

The results of our study also revealed that NAIC in forests and open spaces were highest in summer and autumn, intermediate in spring, and lowest in winter (Fig. 2 a-b). Two mechanisms may explain this pattern. First, cold winter temperatures, short photoperiods, and weak illumination intensity reduce the rate and time of plant photosynthesis, which in turn decreases the NAIC. In the summer and autumn, the photoelectric effect on leaf surfaces, caused by short-wave ultraviolet rays, can increase the bioelectric potential of plants and increase the NAIC (Spanjers 1981; Tikhonov et al. 2004).

Second, because air pollutants have negative effects on NAIC (Retalis and Nastos 2009), higher air pollution in winter, which is typical of the seasonality of air quality in Shanghai, decreased NAIC (Xia et al. 2011). The meta-data about seasonal variations in NAIC (Table 3) verified our results that the values of NAIC did not remain constant throughout the year, but showed clearly seasonal variation with higher values in summer and autumn and lower values in winter and spring.

Comparing NAIC in forests and open spaces

The mean values of NAIC of forests were 442 ions/cm^3, 715 ions/cm^3, 655 ions cm^3 in spring, summer and autumn, respectively. They were significantly higher than those of open spaces, which were 399 ions/cm^3, 633 ions/cm^3, 565 ions/cm^3 in spring, summer and autumn, respectively (Fig. 3). Although there was no significant difference between forests and open spaces in winter, the mean value of forests was 335 ions/cm^3, which was higher than the recorded value of 269 ions/cm^3 of open spaces.

The analysis of the previous studies presented in Table 2 showed that although the measurements of NAIC in all of the 14 studies were taken in different seasons or at different temporal scales, the values of NAIC were always higher in forests than in open spaces. In summary, this result agreed well with our findings.

Three mechanisms may contribute to the difference between forests and open spaces. First, forests have much more leaf biomass capable of promoting electrolysis, thus there are more

sources of NAI than in open spaces. Second, NAI have very short lifetimes (e.g., 110 seconds in Tammet et al. 2006), which limit their long-distance migrations. Third, aromatic substances released by forests can also can promote air ionization and increase NAIC in forests (Shao et al. 2005; Bai and Wu 2008). Therefore, forests have a weak effect on increasing the NAIC of surrounding open spaces. In addition, compared to forests, open spaces have a higher extinction risk of NAI due to their greater exposure to atmospheric environmental air pollution, windy conditions (Retalis 1977; Vana et al. 2008), and intense human disturbance.

Table 2: Comparisons with previous studies for negative air ion concentrations (NAIC) in forests and open spaces.

Country	City	Sampling period	Forests (ions/ cm^3)	Open spaces (ions/ cm^3)	Reference
China	Jiaxing	Jul.2009--Sep.2009	590	470	Zhou et al. 2011
China	Fuzhou	Mar.2010--Apr.2011	617	485	Hu et al. 2012
China	Shanghai	Jul.2006--Aug.2006	500	210	Qin et al. 2008
China	Jiamusi	Jul.2006--Aug.2006	502		Mu and Liang 2009
China	Jilin	Sep.2009	541	205	Yu and Yang 2011
China	Shanghai	Jun.2010--Oct.2010	380		Liu et al. 2011
China	Nanchang	Mar.2005--Apr.2005	435		Guo et al. 2006
China	Hangzhou	Nov.2007--Oct.2008	506		Shi et al. 2009
China	Beijing	Jul.2006	417	285	Wu et al. 2007
China	Nanning	Aug.2001--Oct.2001	225		Fan et al. 2005
China	Yangzhou	Mar.2009--May.2009	426		Ren et al. 2010
China	Beijing	Oct.2007--May.2009	502	171	Li et al. 2011b
Australia	A city	two years	424		Ling et al. 2010
Australia	A city			399	Jayaratne et al. 2008

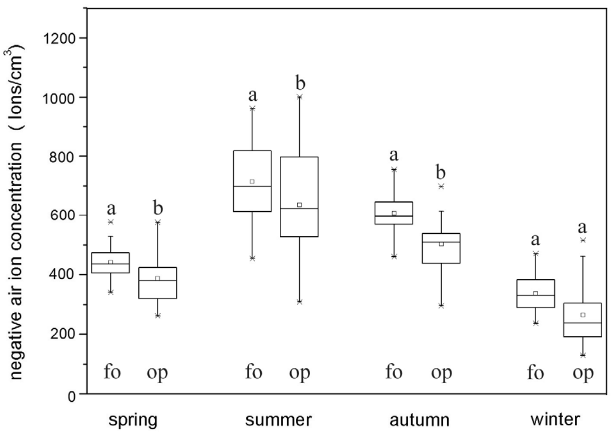

Fig. 3: Seasonal variation in negative air ion concentrations (NAIC) in tree forests (fo) and open spaces (op). Middle point: median; Box: interquartile range (25-75 percentile); Whisker: range (5 and 95% quartiles). One-way ANOVA and Tukey's b test were used test for significance, and significant differences between forests and open spaces are indicated by lower-case letters (p <0.05).

Variation of NAIC along the urban-rural gradient and its determination factors

The spatial variations in NAIC along the urban-rural gradient (Table 4) indicated that there were no significant differences among urban, suburban, and rural areas for forests in all four seasons. Also, there were no significant differences among urban, suburban, and rural areas for open spaces in autumn and winter. However, in open spaces during spring and summer, NAIC were significantly highest in rural areas and lowest in suburban areas.

According to the results of the multiple regression analysis (Table 5), TSP was determined to be the dominant factor affecting NAIC in open spaces during summer. This result could be explained by the ion-induced nucleation mechanisms in the atmosphere (Iida et al. 2006; Vana et al. 2008). It has been reported that air pollution influences the mobility and lifetime of small ions (Retalis 1977). The variations of condensation nuclei will cause wide variations in the lifetime of small ions (Law 1963). NAIC decrease considerably or even fall to zero in the polluted air of cities, due to the ion-induced nucleation mechanisms in the atmosphere (Tikhonov et al. 2004).

In spring, air temperature and air humidity were the dominant factors affecting NAIC in open spaces. Air temperature and air humidity both showed a positive correlation with NAIC (Table 5). Air humidity explained more of the variation in NAIC than air temperature.

The relationship between NAIC and air temperature were not consistent with the results of previous studies (Table 6). Previous studies (Wu et al. 2001; Chen et al. 2006; Ji et al. 2007; Zhang et al. 2008; Mu and Liang 2009) showed that NAIC were negatively correlated with air temperature. It is worthwhile to note that all of these conclusions were based on measurements taken over one to several days with clear weather, and the air temperature variation was minor in all these studies. However, similar to our research, the studies that were based on one to several years of fixed-point observations, showed a wide variation in air temperature, and indicated that NAIC were positively correlated with air temperature (Peng et al. 2008; Xu et al. 2008). Moreover,

Wang (2003) clearly showed a significant negative correlation between NAIC of urban green areas and air temperature over the course of one day, but showed a significant positive correlation when this relationship was considered over the course of one year.

Table 3: Comparisons with previous studies for seasonal variation in negative air ion concentrations (NAIC).

Country	Site	Sampling period	Seasonal variation	Reference
China	Beijing Botanical Garden, Fragrance Hill, the Summer Palace	Oct.2007--Sep.2008	Summer>Autumn>Spring>Winter	Li et al. 2010b
China	Huaxi Park	Jul.2004--May.2009	Summer>Autumn>Spring>Winter	Yang et al. 2006
China	The Sanatoriums in the West Lake Scenic Area	Dec.2008--May.2009	Spring>Winter	Lin and Jin 2010
China	Six Plantations and one wasteland	Apr.2009--Sep.2009	Summer>Autumn>Spring	Li et al. 2010a
China	Jigong Mountain	Jun.2007--May.2010	Summer>Autumn>Spring>Winter	Li et al. 2011a
China	Nanhu Park, Zhongshan Park, Wanshi Botanical Garden	Jul.2007--Mar.2008	Summer>Autumn>Spring>Winter	Pan et al. 2009
China	Yulu Mountain	Oct.2003--Sep.2004	Autumn>Summer>Spring>Winter	Wu et al. 2006
China	Tianmu Mountain	Sep.2005--Aug.2006	Summer>Spring>Autumn>Winter	Zhang et al. 2008
China	Central South Forestry College	Jul.1996--Apr.1997	Summer>Autumn>Spring>Winter	Wu et al. 2001
China	Laoshan timberland	Apr.2010--Dec.2010	Summer>Autumn>Spring>Winter	Liu et al. 2012
Greece	Athens	1968--1984	Autumn>Winter>Summer>Spring	Retalis and Nastos 2009

Table 4: Comparison of seasonal negative air ion concentrations (NAIC; Values are presented as mean ± SD.) of forests and open spaces among urban, suburban and rural areas. One-way ANOVA and Tukey's b test were used to test for significance, and significant differences among three regions are indicated by lower-case letters (p <0.05).

	Region	Spring	Summer	Autumn	Winter
Forests	Urban	456±92a	763±223a	658±68a	330±88a
(ions/ cm^3)	Suburban Rural	424±50a	673±113a	607±83a	351±69a
		457±61a	738±62a	560±71a	313±59a
Open spaces	Urban	363±51ab	632±287ab	550±128a	215±108a
(ions/ cm^3)	Suburban	357±55a	567±124a	464±83a	271±95a
	Rural	463±109b	760±67b	523±65a	303±145a

Table 5: The results of a multiple regression analysis on factors affecting negative air ion concentrations (NAIC) of open spaces in spring and summer. B: regression coefficients; Beta: standardized regression coefficients. Larger Beta values indicate a greater contribution of independent variables to the dependent variable.

	Beta	B	Standard error of B	t	p-level
a. spring	R=0.777	R^2=0.604	Adjust R^2=0.538	p <0.001	
Intercept		-2.660	0.714	-3.725	0.003
Air temperature	0.877	0.615	0.148	4.160	0.001
Air humidity	0.626	0.311	0.105	2.967	0.012
b. summer	R=0.664	R^2=0.441	Adjust R^2=0.398	p <0.001	
Intercept		1.416	0.291	4.861	0.000
TSP	-0.664	-0.239	0.075	-3.200	0.007

Table 6: Comparisons of the relationship between negative air ion concentrations (NAIC) and air temperature with previous studies.

City	Site	Sampling period	Temperature range (°C)	Relationship between NAIC and temperature	Reference
Guangxi	Resorts in primeval forest	30th Jul. 1996−1st Aug. 1996	18.1−25.1	negative correlation	Wu et al. 2001
Shanghai	botanic garden	19th Mar. 2006	6.1−13.2	negative correlation	Chen et al. 2006
Shenyang	Qipan mountain	Jul.2007−Aug. 2007	17−30	negative correlation	Ji et al. 2007
Zhejiang	Tianmu mountain	Jun.2006−Aug. 2006	23.5−26.8	negative correlation	Zhang et al. 2008
Guangzhou	Maofeng mountain	2004−2007	10−30	positive correlation	Xu et al. 2008
Shanghai	East China Normal University	Jan.2007−Dec.2007	8−33	positive correlation	Peng 2008
Jilin	Beihua university	16th May. 2002−17th May.2002	8.9−19.5	negative correlation	Wang 2003
Jilin	Beihua university	Sep.2001−Aug.2002	-10.8−24.2	positive correlation	Wang 2003

Most studies monitor field sites, including our study, and indicated that there was a significant positive correlation between NAIC and air humidity (Table 7). Wang et al. (2003) drew a similar conclusion by using laboratory experiments that found a significant positive correlation between NAIC and air temperature and also between NAIC and air humidity. They also pointed out that the influence of air humidity on NAIC is greater than the influence of air temperature. In contrast, some studies (Duan 2007; Reiter 1985) showed significant negative correlations between NAIC and air humidity in foggy weather. This effect of relative air humidity on NAIC was caused indirectly by an increase in nuclei condensation radius and an increase of combination rate, which lead to a decrease in small ions mobility (Retalis and Nastos 2009).

Table 7: Comparisons of the relationship between negative air ion concentrations (NAIC) and air humidity with previous studies.

City	Site	Sampling period	Humidity range	Relationship between NAIC and humidity	Reference
Guangxi	Resorts in primeval forest	30th Jul. 1996–1st Aug.1996	83%–99%	positive correlation	Wu et al. 2001
Shanghai	botanic garden	19th Mar. 2006	54%–70%	positive correlation	Chen et al. 2006
Shenyang	Qipan mountain	Jul. 2007–Aug. 2007	60%–96%	positive correlation	Ji et al. 2007
Guangzhou	Maofeng mountain	2004–2007	50%–90%	positive correlation	Xu et al. 2008
Zhejiang	Tianmu mountain	Jun. 2006–Aug. 2006	86%–96%	positive correlation	Zhang et al. 2008
Jiamusi	Xinglinhu park, Jiamusi University	Mar. 2006–Feb. 2007	20%–80%	positive correlation	Mu and Liang 2009
Hefei	Dashu mountain	Apr. 2004–May. 2004	40%–84%	positive correlation	Wei et al. 2006
Shanghai	East China Normal University	Jan.2007 –Dec. 2007	38%–66%	positive correlation	Peng 2008
Anhui	Huang mountain	20th Apr. 2002–20th May. 2002		negative correlation	Wang 2003
Beijing	urban green space	Mar. 1999–May. 1999		negative correlation	Ye and Wang 2000

Previous studies showed that either a positive correlations (Chen et al. 2006; Ye and Wang, 2000) or a negative correlation(Vana et al. 2008) or no correlation(Wang 2004; Duan 2007) exists between wind speed and NAIC. Wind speed influences NAIC indirectly by influencing other environmental factors; for example, it can produce more NAI by increasing the air friction when wind speed is greater (Wu et al. 2007). In our study, it indicated that there was a significant positive Pearson correlation between wind speed and TSP in summer (R^2=0.463, p=0.000), so the influence of wind speed on NAIC may be included in the impact of TSP.

In our study, the number of people passing within 5m of the measurement points is less than 14.6 person every minute, which is much lower than the number(500 person every minute) of a previous study (Zeng et al. 2007) that concluded the significant relationship between NAIC and population flow rate. This may be the main reason that there is no correlation between them in this study.

Conclusions

The NAIC was mainly affected by both its source and the atmospheric environment. Urbanization has greatly changed the natural environment, including the composition of NAI sources and the atmospheric environment, which probably altered NAIC in cities. However, our knowledge on this topic is limited, for few researchers are focus on this theme. Therefore, we analyzed the spatio-temporal pattern of NAIC in parks along the urban-rural gradient in Shanghai, which is one of the biggest cities in China and has experienced rapid urbanization over the past 30 years.

Our results showed that NAIC clearly displayed seasonal variation with peak values during summer and lowest values in winter, which is consistent with all previous studies conducted in nature and other cities. On the other hand, NAIC showed significant differences along the urban-rural gradient in open spaces during spring and summer, but no markedly different values in forests during all seasons. All of these results suggest that 1) urbanization could induce variation in NAIC along the urban-rural gradient but may not change the temporal variation pattern; and 2) the effects of urbanization on NAIC were limited in non-vegetated or less-vegetated sites, such as open spaces, but not in well-vegetated areas, such urban forests. This indicated that urban greening, especially urban forest, has a significant resistance to the effect of urbanization on NAIC.

Moreover, we found that the differences in NAIC along the urban-rural gradient were primarily determined by air pollution like TSP, and climate, such as air humidity and air temperature, which were tightly correlated with the urbanization process of Shanghai and its impacts on environment. As one of biggest cities in China, Shanghai has exhibited a very rapid circle-sprawl urbanization pattern originating from the original urban center since the late 1970s.

After nearly 20 years of development, the urban area reached a great degree of urbanization in the 1990s and suburbanization has arisen since that time. The industrial center has gradually shifted from urban areas to suburban and rural areas, and tertiary industries dominated the urban areas. The proportion of industrial output in urban areas dropped from 70.3% in 1983 to 11.8% in 2005 (Shanghai Statistical Bureau 1983-2006). As a result, the population density in suburban areas increased from 1,407 person per km^2 in 1983 to 2,469 person per km^2 in 2005 (Shanghai Statistical Bureau 1983–2006). To accommodate this increasing population and effectively providing necessary services and management facilities, large areas of land were taken over for public infrastructure, housing, traffic, and commercial uses (Yin

et al. 2011).

Therefore, the environment in suburban areas deteriorated in response to the suburbanization. The TSP, NOx, and SOx concentrations in the air have increased from1998~2005 (Xia et al. 2011), and the urban heat island effect has occurred with more frequency in suburban areas (Zhang et al. 2010). Conversely, the air quality in urban areas improved as the reduced industrial production increased greening areas and massive restoration measures occurred (Zhao et al. 2006). Meanwhile, rural areas have been dominated by cropland and vegetation with low population densities and therefore the best environment quality. As a consequence, suburban areas with poor air quality and hotter and drier climates displayed the lowest NAIC.

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